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ADP023718

TITLE: Trusted Computing Technologies for Embedded Systems and Sensor Networks

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TITLE: Proceedings of the ARO Planning Workshop on Embedded Systems and Network Security Held in Raleigh, North Carolina on February 22-23, 2007

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The following component part numbers comprise the compilation report:
ADP023711 thru ADP023727

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Trusted Computing Technologies for Embedded Systems and Sensor Networks

Adrian Perrig
Carnegie Mellon University

Motivation

- Embedded processors closely integrated into the fabric of everyday life
  - Anything with a powerplug is likely to already be equipped with an embedded processor
  - Additional battery-operated embedded devices are emerging (e.g., thermometers)
- Embedded processors enable new features
  - Unfortunately, features increase complexity
- Steady increase in complexity results in bugs, which require software updates to fix
- **Scary: Embedded systems with network access and code update features**

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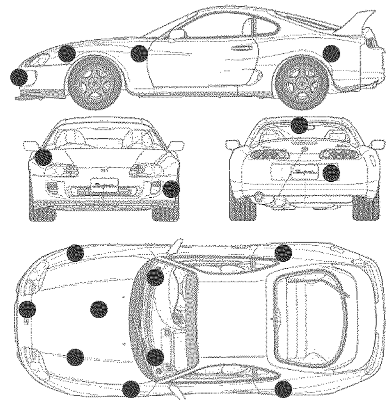
Example: Vehicular Embedded Networks

- Technology trends
  - Steady increase in number and complexity of processing units
    - GPS, in-car entertainment, safety systems
  - Car communication systems
    - DSRC, cellular technologies, BlueTooth, USB
- Security challenges:
  - Vehicular malware!



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Challenges

- Ensure integrity of code executing on embedded device
  - Ensure result obtained was created by correct code
- Secure code updates
- Recovery after attack
  - Re-establish code integrity
  - Re-establish secret and authentic keys

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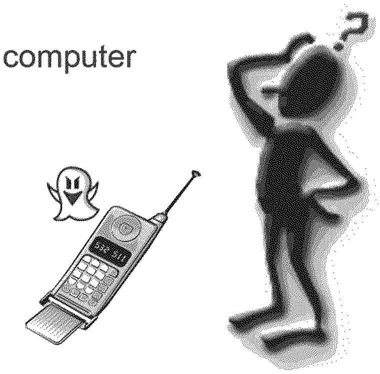
How can we trust our devices?

- How do we securely use (potentially) compromised devices or devices we don't trust?
  - Cell phone, PDA, or car computer



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Attacker Model

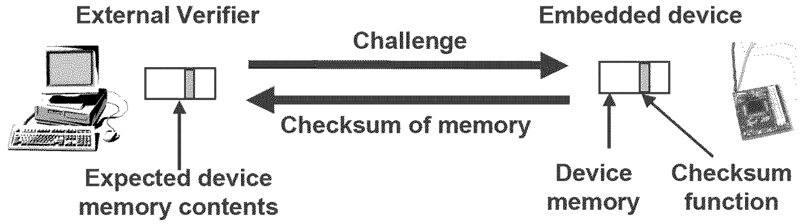
- Attacker controls software on embedded system
  - Complete control over OS, memory
  - Injection of malicious code
- No hardware modifications, verifier knows HW spec
  - Hardware attacks are much harder to perform, requires physical presence
  - Very challenging to defend against
- In this talk, assume verifier controls network, such that verified device cannot contact external helpers

Approaches to Ensure Code Integrity

- Hardware-based
  - Fixed ROM-based code
    - Cannot support code updates
  - TCG
    - Requires extra hardware, potentially high unit cost
- Software-based
  - Software-based attestation
    - Need to guard against proxy attack

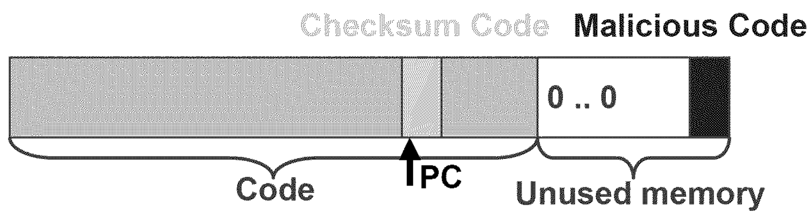
Software-based Attestation Overview

- External, trusted verifier knows expected memory content of device
- Verifier sends challenge to untrusted device
  - Assumption: attacker has full control over device's memory before check
- Device returns memory checksum, assures verifier of memory correctness



ICE: Indisputable Code Execution

- Add chksum function execution state to checksum
  - Include program counter (PC) and data pointer
- In memory copy attack, one or both will differ from original value
- Attempts to forge PC and/or data pointer increases attacker's execution time



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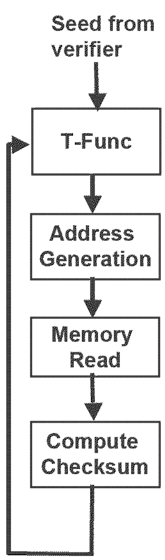
ICE Assembler Code



Generate random number using T-Function

```
mov r15, &0x130
mov r15, &0x138
bis #0x5, &0x13A
add &0x13A, r15
```

Load byte from memory

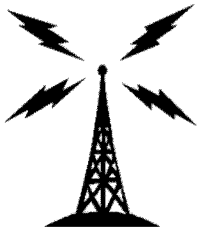
```
add r0, r6
xor @r13+, r6
```

Incorporate byte into checksum

```
add r14, r6
xor r5, r6
add r15, r6
xor r13, r6
add r4, r6
rla r4
adc r4
```

ICE Protocol

Wireless link

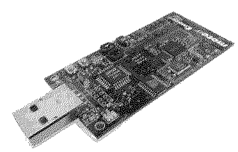


Base station

t_1: nonce, input

t_2: cksum

output



Node

- Successful verification if:
  $t_2 - t_1 <$ expected time
  and
  cksum == exp. cksum

nonce → Verf. Func. → cksum

input → Target Code → output

ICE Verification Function

- Implemented as self-checksumming code
  - Computes checksum over its own instructions
- Set up untampered execution environment
  - CPU state for atomic execution
  - E.g., turn off interrupts
- Compute checksum
  - Using memory contents and CPU state
- Checksum verifies integrity and correct set-up of execution environment

Verification Function

Target Code

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ICE Properties

- Given target code T, verifier obtains property that sensor node S correctly executes T, untampered by any other (malicious) code potentially present on S
- By incorporating node ID into checksum computation, we can authenticate response

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Key Establishment

- How to establish a shared secret?
  - Attacker may know entire memory contents of a newly shipped node
  - After a node has been compromised, attacker may have altered authentic public keys or knows secret keys
  - Without authentication Diffie-Hellman protocol is vulnerable to man-in-the-middle attack:
    - A → B: g^a mod p
    - B → A: g^b mod p

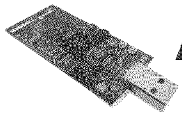
Problem Formulation

- Given nodes in a sensor network, how can any pair of nodes establish a shared secret without any prior authentic or secret information?
- In theory, this is impossible … because of active MitM attack
- Assumptions
  - Attacker cannot compute faster than sensor node
  - Each node has a unique, public, unchangeable identity stored at a fixed memory address
  - Secure source of random numbers

ICE Key Establishment

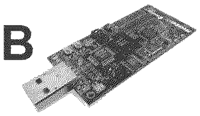
- Intuition: leverage ICE to compute checksum faster than any other node, and use that checksum as a short-lived shared secret
- Challenge: how to use short-lived shared secret to bootstrap long-lived secret?
  - Authenticate Diffie-Hellman public key

First Attempt



A

B



Pick random a

Compute $g^a \bmod p$

t_0: $g^a \bmod p$ →

Pick random b

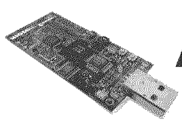
Compute $g^b \bmod p$

$g^a \bmod p$ = challenge

Compute cksum c

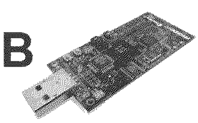
← t_1: $g^b \bmod p$, MAC(c, $g^b \bmod p$)

Second Attempt



A

B



Pick random a

Compute $g^a \bmod p$

t_0: $g^a \bmod p$ →

$g^a \bmod p$ = challenge

Compute cksum c

Pick random b

Compute $g^b \bmod p$

← t_1: $g^b \bmod p$, MAC(c, $g^b \bmod p$)

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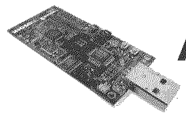
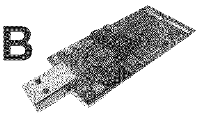
Guy Fawkes



A

B



Goal: A and B can authenticate each other's messages

A	B
Pick random v_2	Pick random w2
$v_1 = H(v_2)$, $v_0 = H(v_1)$	w_1=H(w_2), w_0=H(w_1)
one-way chain: $v_0 \leftarrow v_1 \leftarrow v_2$	$w_0 \leftarrow w_1 \leftarrow w_2$
Assume: A knows authentic w_0	B knows authentic v_0

$$A \xrightarrow{v_1,\ M_a,\ MAC(v_2, M_a)} B$$

$$A \xleftarrow{w_1,\ M_b,\ MAC(w_2, M_b)} B$$

$$A \xrightarrow{v_2} B$$

$$A \xleftarrow{w_2} B$$

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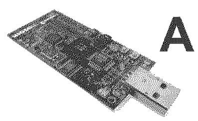
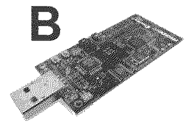
ICE Key Establishment



A

B



Pick random a, $g_a = g^a$ mod p

Compute $g'_a = H(g_a)$, $g''_a = H(g'_a)$, $g''_a \leftarrow g'_a \leftarrow g_a$

$$A \xrightarrow{t_0:\ g''_a} B$$

g''_a = challenge

Compute cksum c

$w_0 \leftarrow w_1 \leftarrow w_2$

$$A \xleftarrow{t_1:\ w_0\ MAC(c, w_0)} B$$

random b, g^b mod p

$$A \xrightarrow{g'_a} B$$

$$A \xleftarrow{w_1,\ g^b \bmod p,\ MAC(w_2,\ g^b \bmod p)} B$$

$$A \xrightarrow{g_a} B$$

$$A \xleftarrow{w_2} B$$

Summary: ICE Key Re-Establishment

- Protocol can prevent man-in-the-middle attacks without authentic information or shared secret
- Attacker can know entire memory content of both parties before protocol runs
- Forces attacker to introduce more powerful node into network, prevents remote attacks
- Future work: relax strong assumption that attacker cannot compute faster

Summary

- Software-based attestation provides interesting properties, but many challenges remain
  - Defeat proxy attacks in wireless environments
  - Extend properties to general computation
  - Build systems with perfect detection of code integrity attacks
  - Recover from malicious code infection
  - Provide human-verifiable guarantees
- Study use of hardware-based support
  - Determine minimal hardware requirements to provide embedded systems security